2012 DOE Solid-State Lighting
MANUFACTURING R&D WORKSHOP
June 13–14, 2012 • San Jose, California

Solid-State Lighting Manufacturing R&D Workshop

REPORT

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

August 2012

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1. Introduction

Two hundred lighting industry leaders from across the country met in San Jose, CA, on June 13–14, 2012, at the fourth annual Solid-State Lighting (SSL) Manufacturing R&D Workshop, hosted by the U.S. Department of Energy (DOE). Representatives from every link in the supply chain—chip makers, luminaire manufacturers, material and equipment suppliers, packagers, luminaire testers, and makers of testing equipment—gathered to share insights, ideas, and updates. The workshop is a key component of an initiative launched by DOE in 2009 to enhance the quality and lower the cost of SSL products through improvements in manufacturing equipment and processes, and to foster a significant manufacturing role in the U.S. This year in San Jose, attendees explored a wide range of related topics and focused on reexamining and updating the DOE Manufacturing R&D Roadmap.

Nearly 200 participants attended the fourth annual SSL Manufacturing R&D Workshop, hosted in June by DOE.

2. A Role for U.S. Manufacturing

2.1 Welcome

DOE SSL Portfolio Manager James Brodrick kicked off Day 1 by emphasizing that collaboration and a common framework of priorities are essential to moving SSL forward. “Cost reductions are key and don’t happen easily or automatically,” he said. “We need to rethink the way things are done.” Observing the window of opportunity to establish a U.S. role in SSL manufacturing, Brodrick raised the question of what role makes the most sense. He noted that DOE’s SSL manufacturing R&D initiative aims to encourage a U.S. role in SSL manufacturing, as well as to accelerate cost reductions and improve product quality through equipment and process improvements.

Christopher Ruud of Cree shared insights on U.S. manufacturing in the competitive and fast-moving LED market.

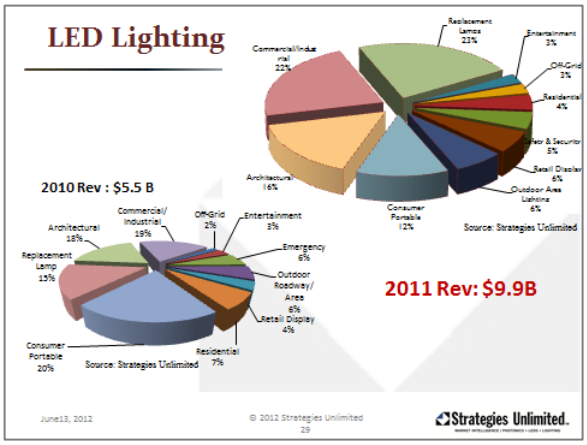
2.2 Competing in the Global Market

Christopher Ruud of Cree, Inc., followed with a talk about creating a globally competitive manufacturing environment in the U.S. He illustrated this with examples from Ruud Lighting, the division of Cree that he heads, which was acquired in August 2011 and continues to manufacture domestically. Ruud noted that LEDs are still in the process of evolving, so manufacturers have to be ready

for shorter product life-cycles. He reviewed some of the advantages of manufacturing domestically, such as being closer to the U.S. market; cutting down on lead time; and avoiding being stuck with unsaleable products that are shipped in from overseas in large quantities and become superseded before they sell out. Ruud said it is a myth that products cannot be manufactured in the U.S., noting that highly automated manufacturing negates the advantage of low overseas labor rates.

2.3 Global Manufacturing Trends

Vrinda Bhandarkar of Strategies Unlimited provided a look at global manufacturing trends in lighting. Citing DOE's *2010 U.S. Lighting Market Characterization* report, she reported that of the country's 8.2 billion lamps, roughly 45 percent are incandescent, 29 percent linear fluorescent, and 19 percent compact fluorescent—with just 1.4 percent falling into a catch-all category that includes LEDs. Reviewing trends in LED packaging, Bhandarkar observed that the LED count is dropping fast, with prices dropping even faster, and that there is major growth in the use of low- and mid-power LEDs for ambient lighting applications. She noted that LED lighting was a $9.9 billion industry in 2011—with replacement lamps accounting for 23 percent, commercial/industrial 22 percent, and architectural 16 percent—and that revenue is expected to increase steadily to about $22 billion in 2016.



The LED lighting market not only grew but also evolved from 2010 to 2011.

3. Rethinking the Manufacturing Process

A panel moderated by Morgan Pattison of SSLS, Inc., focused on rethinking SSL luminaire manufacturing. Mark Hand of Acuity Brands Lighting noted that the goal of reducing manufacturing costs is complicated by new testing requirements. He acknowledged that the industry has changed a great deal in the past few years, that regulatory testing alone is no longer sufficient, and that validation testing is needed to ensure quality and reliability. But Hand said that having so many testing requirements—caused in part by the explosion in LED lighting product codes—requires a great deal of time and money from manufacturers, and some of that testing may be redundant. He expressed a hope that the DOE SSL program could help coordinate and streamline the various testing requirements to reduce the burden.

Craig Fenske of Philips Lighting Systems & Controls offered his company's perspective on manufacturing the L Prize®-winning LED replacement for the 60-watt incandescent bulb. He described how the prizewinning lamp, which went into production in the first quarter of 2012, is assembled in the U.S. by a strategic partner. Fenske compared traditional glass lamp manufacturing with that of the L Prize-winning product. He noted that after many decades of production, traditional glass lamp manufacturing is highly refined and automated, and tested with just a functional light-up of the product, whereas the new lamp combines state-of-the-art designs and electronic components

that are assembled into a new and much more complex product than the simple filament-based light bulb.

Nikhil Taskar, right, of WAC Lighting answered an audience question about manufacturable luminaire design. Also pictured: Mark Hand, Acuity Brands Lighting (left) and Craig Fenske, Philips (center).

Nikhil Taskar of WAC Lighting discussed trends in manufacturable designs for SSL luminaires, focusing on manufacturability for high volume based on modular approaches. He touched on the light engines, the construction of the luminaire, the electronics, and the optics. Noting that the total cost of ownership for SSL is still heavily driven by the initial upfront cost, Taskar explored the blending of large-area light sources with high-luminance, highly directional light engines that leverage the strength of LEDs. He observed that from a manufacturer's standpoint, bringing those two different solid-state light sources together into a luminaire poses a formidable challenge. He also pointed out that using modular building blocks that are individually amenable to high-volume manufacturing with automation will drive down the cost of the overall product.

Question-and-Answer Session

One attendee asked Hand how the increased testing affects Acuity luminaires. Hand replied that he did not have exact price-increase figures, but he estimated that the number of required tests has tripled, causing Acuity to roughly double its staff. When asked how switching to LEDs from a different supplier would affect an SSL manufacturer's cost, Fenske said it would entail a significant cost increase, because LEDs from different manufacturers differ on such performance parameters as light output and efficacy. "Essentially, it would be a different product," he said. Regarding the integration of drivers and control electronics, Taskar was asked if there has been any discussion about providing a port for the driver and a small interface. He replied that this was a good question, and that the challenge is keeping a basic control and the regulation of the signals at the radio-frequency end, while keeping the power-handling end within the electromagnetic interference specification.

4. Getting Everyone on the Same Page

4.1 Harmonizing Performance Requirements and Testing

Marc Ledbetter of Pacific Northwest National Laboratory (PNNL) gave an update on efforts by the International Energy Agency (IEA) to harmonize LED test procedures, testing capability, and performance requirements among different countries. He explained that these efforts are carried out by the IEA's Efficient Electrical End-Use Equipment Solid State Lighting Annex, which is presently funded by the U.S., the U.K., France, Australia, Denmark, Sweden, Japan, and the Netherlands. Ledbetter noted that the goal is to provide governments with the tools to assess the performance of SSL, inform energy-efficient lighting policies, and harmonize test procedures and laboratory

accreditation to increase confidence in solid-state lighting. He reviewed the progress that has been made to date in the areas of quality assurance, testing, and international accreditation.

4.2 SEMI's Standards Initiative

Tom Morrow of SEMI discussed standards development for LED manufacturing.

Tom Morrow of SEMI next gave a talk about the development of standards for LED manufacturing. He updated the audience on SEMI's SSL manufacturing standards initiative, which includes task forces on high-brightness LEDs, sapphire impurities and defects, and environmental health and safety, as well as hardware and software working groups on factory automation interfaces. Morrow advocated that the U.S. government increase DOE funding for SSL R&D and manufacturing infrastructure development, establish the R&D tax credit on a long-term basis to aid in tax and investment planning, revive the Advanced Energy Manufacturing Tax Credit, and create a federal Green Bank to supplement LED and other green energy projects, particularly for manufacturing. "We need to be forward-looking, not backward-investing," he said.

5. The DOE SSL R&D Program

5.1 Research Updates

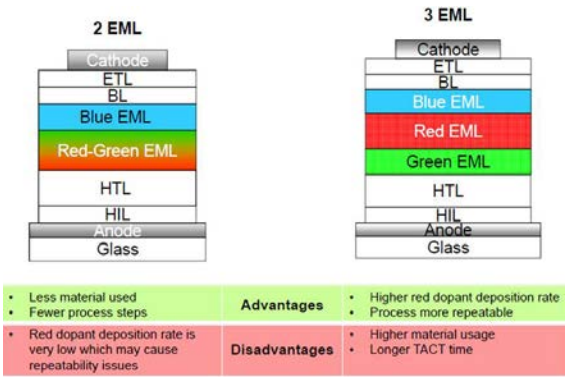
Brodrick began the next session with an overview of DOE's SSL manufacturing R&D portfolio, budget, and areas of focus. He stated that DOE SSL program funding is impacted by congressional direction, and that Congress has directed DOE to put most of its 2012 SSL R&D emphasis on manufacturing. He added, however, that DOE will continue to support SSL Core Technology Research and Product Development, whose solicitations will be postponed until the next fiscal year, to gain a better idea of available funding. Brodrick said that 2012 will be the third round of DOE SSL manufacturing funding, and that the first-round projects are wrapping up—the members of this first "graduating class" are among those reporting their results at the workshop.

Brian Dotson of the National Energy Technology Laboratory then introduced the recipients of DOE's current SSL manufacturing R&D awards, who gave brief updates on their DOE-funded projects as an introduction to the project posters at the evening poster session/reception. These projects range in focus from epitaxy tools to automated defect detection systems to the design and setup of OLED manufacturing pilot lines, and reflect DOE's commitment to accelerate the adoption of SSL technology through manufacturing improvements that reduce costs and improve quality.

- Mike Hack of Universal Display Corporation (UDC) discussed a project with Moser Baer Technologies (MBT) to set up a pilot OLED manufacturing line in the U.S. that will provide prototype lighting panels to U.S. luminaire manufacturers and facilitate the growth of the embryonic OLED lighting industry. Located in Canandaigua, NY, the facility will be built and operated by MBT and utilize UDC's phosphorescent OLED technology. UDC will transfer its technology into the pilot line and refine the cost models. Hack said the cleanroom is near completion and the project—which is based on the high-throughput processing of 150 mm x 150 mm glass substrates—is on track to begin production in 2012.

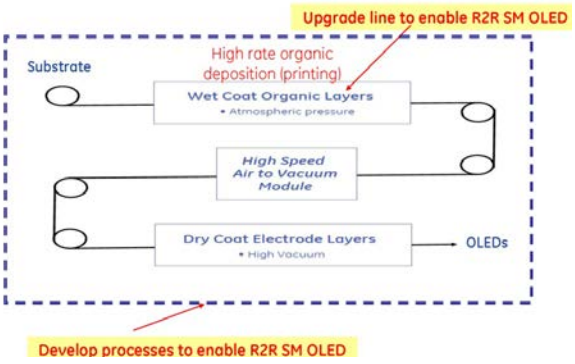
The cleanroom is near completion at the Canandaigua, NY, facility where UDC's pilot OLED manufacturing line will be located.

- Gopalan "Raj" Rajeswaran of MBT talked about how his company is leveraging its experience with OLED displays to design and build the abovementioned Canandaigua facility, which will use UDC's proprietary OLED technology in the low-cost production of OLED panels. The goals are to improve manufacturing tolerances in production equipment as well as processes, and to implement quality control methods and tools to increase yield (to >90 percent by 2015) and minimize the need for binning. Studies have been performed on a white OLED stack, to understand the effect of layer thickness and dopant on the color of the light emitted. MBT is working to increase light extraction of the OLED panels by making improvements in the glass substrate, and key process variables for low-cost integrated glass substrates have been identified.



Studies were performed on a white OLED stack to understand the effect of layer thickness and dopant percentage on the color of the light emitted.

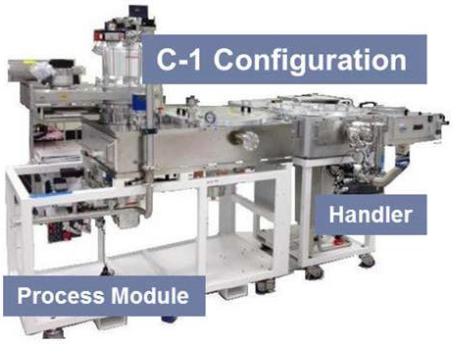
- Jerry Liu of GE Global Research described his company's development of a roll-to-roll solution-processing method for producing small-molecule OLEDs. The idea is to reduce OLED costs while still getting high performance. The method, which would be suitable for commercial applications, involves a machine printing all four organic semiconductor layers, in liquid form, one right after the other on a roll of flexible substrate, similar to the way ink is printed on



GE developed an efficient method of printing OLED semiconductor layers on a roll of flexible substrate, similar to the way ink is printed on newspapers.

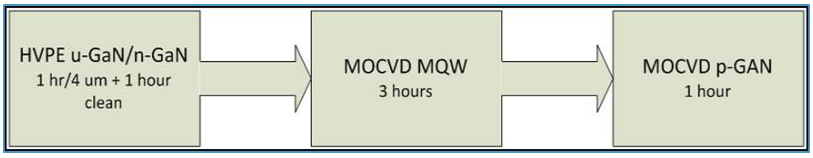
newspapers. GE is trying to perfect the technique, with the goal being to equal the performance of OLEDs made by batch-processing. Liu said they have found a low-cost substrate and are testing its moisture-barrier properties. The next step is to minimize the footprint by making the machine smaller in size.

- Frank Cerio of Veeco Instruments discussed his company's attempts to reduce epitaxy costs and increase LED efficiency by developing a sputtering (physical vapor deposition) tool for depositing aluminum nitride buffer layers on LED substrates. An alternative to MOCVD that involves using plasma and a magnet to deposit the buffer layer, sputtering can be used on both sapphire and silicon substrates. A "greener" process than metal-organic chemical vapor deposition (MOCVD), it does not use toxic chemicals and has the potential to use fewer materials. Cerio explained that the objectives of the project are to reduce epitaxy costs by 60 percent due to higher throughput, lower defect density, and reduced yield loss from wafer bow and temperature variations.



Veeco Instruments hopes its sputtering tool for depositing buffer layers on LED substrates will reduce epitaxy costs by 60%.

- Vivek Agrawal of Applied Materials talked about his company's progress in developing an advanced epitaxial growth system for gallium nitride LED devices that will decrease operating costs, increase internal quantum efficiency, and improve binning yields. The standard epitaxy method is to use a single MOCVD chamber for each of the three principal layers of an LED structure, which slows down the production process and requires costly and time-consuming cleaning after each step. Applied Materials uses a separate chamber for each layer, which facilitates optimization, and a self-cleaning process adds further efficiencies. In addition, a faster and cheaper new technology, hybrid vapor phase epitaxy (HVPE), is used instead of MOCVD for one of the steps.



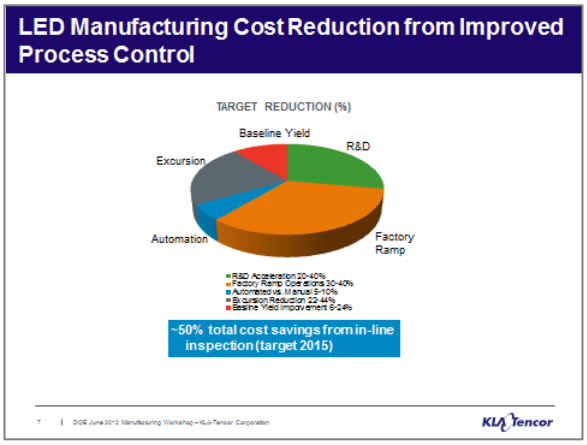
The sequential 3-chamber process of Applied Materials' advanced epitaxial growth system reduces cycle time to 3.3 hours per run.

- Jay Montgomery of Veeco Process Equipment and Mike Coltrin of Sandia National Laboratories described how their companies are collaborating to drive down the cost of HB LEDs by implementing process simulation tools and temperature control methods to increase MOCVD yield, and by improving temperature measurement and control. Veeco and Sandia are working to reduce the cost of ownership of the deposition equipment by, for example, using a heated flow flange, which reduces the consumption of the expensive flow gases (ammonia, nitrogen, hydrogen, and the metalorganics) by 40 percent. Two different types of pyrometer are

also being tested to control the temperature, which helps determine the color of the LED. The goal is to reduce the epitaxy cost by 75 percent. The project has helped produce the MaxBright™ multireactor system, which incorporates many of these features.

Veeco's MaxBright multireactor system will help lower the cost of manufacturing high-brightness LEDs by improving throughput, growth uniformity, yield, and temperature stabilization.

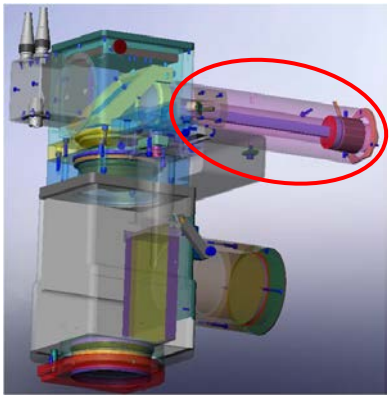
- Srini Vedula of KLA-Tencor Corporation discussed the use of automated inspection to increase yield and decrease defects and cost in LED manufacturing. The company has developed an in-line inspection tool, the Candela 8620, which can identify defect sources early in the LED manufacturing process. Incorporating both hardware and software components, it can be used at various stages: during new process development, to find out where defects such as micropits and microcracks occur; to reduce the time it takes to ramp up production; and in full production, to detect and reduce "excursions" (departures from the desired outcome). Philips Lumileds is helping with the project by testing samples and doing beta validation of the tool. The goal is to cut manufacturing costs in half by 2015.



KLA-Tencor expects that its in-line inspection tool will be able to cut LED manufacturing costs in half by 2015.

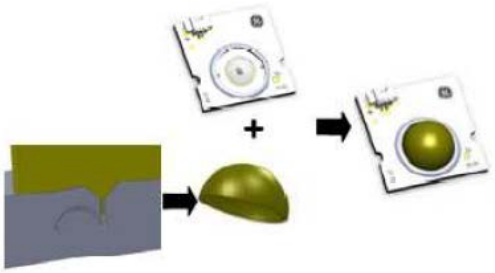
- Andy Hawryluk of Ultratech Inc. talked about his company's project adapting an existing lithography tool for use in manufacturing high-brightness LEDs, and in the process reducing capital expenditure and cost of ownership while increasing throughput and yield. The tool was designed for the semiconductor industry and uses projection lithography, which Hawryluk explained is more cost-effective than the usual alternative, proximity print lithography. He noted that while proximity print lithography is fine for R&D and low-volume manufacturing, it is not suitable for mass production.

  Hawryluk stated that the resulting product, which Ultratech is already marketing to the industry, can pay for itself in three to six months and generate up to $4 million a year in revenue.



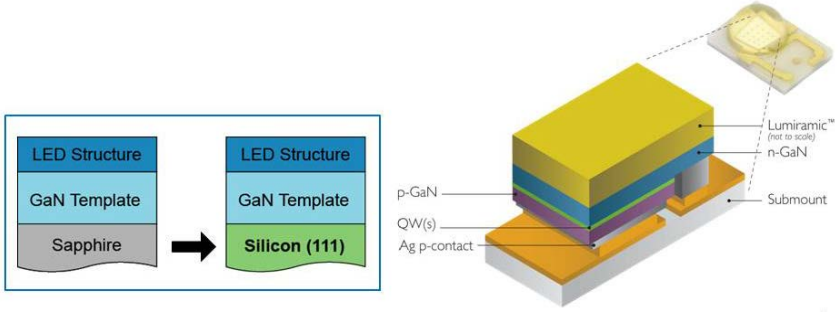
Ultratech's design for a high-power LED illuminator (mechanical interfaces circled) is being adapted from a lithography tool to lower the manufacturing costs of high-brightness LEDs.

- Anirudha Deshpande of GE Lighting Solutions discussed his company's development, design, and piloting of advanced manufacturing methods for warm-white general-illumination LEDs, based on remote-phosphor techniques. Phosphor is a critical element in LEDs because it converts blue light into warm-white light. With the remote-phosphor method, the phosphor forms a dome over the chip instead of being directly deposited on it. Phosphor is expensive, and GE Lighting Solutions is reducing the phosphor content by mixing it with a polymer carrier so that it is injection-moldable. They have also scaled the process up so it can be used in their line manufacturing. Deshpande said the phosphor content has been reduced by 75–80 percent, and they are seeing a color shift of less than one MacAdam step after 6,000 hours, which is better than with phosphor-on-chip.



GE chose phosphor molding as the remote-phosphor method for manufacturing warm-white general illumination LEDs.

- John Epler of Philips Lumileds described his company's exploration of the use of nitride epitaxy on 150mm silicon substrates to produce low-cost, warm-white, high-performance general-illumination LEDs. Most LEDs are made with sapphire substrates, but silicon is much cheaper and easier to obtain. Philips Lumileds is attempting to adapt the use of silicon to the manufacture of LEDs, drawing upon the knowledge base and depreciated equipment of the computer industry, which has been using silicon substrates for decades. Epler explained that silicon is not well-matched with gallium nitride (GaN) and tends to crack during the drying process, but he said growing the GaN compressively strained can remedy that. He stated that the project shows that there are no major barriers to switching to silicon substrates.

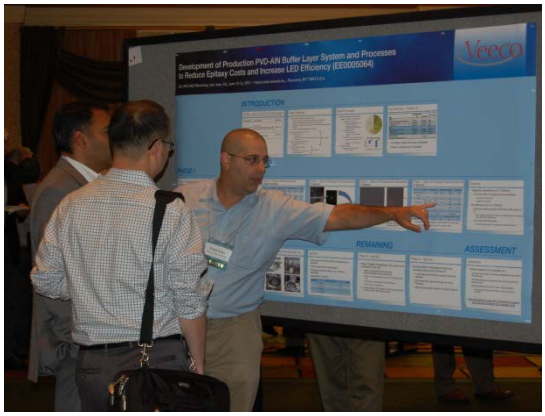


Philips Lumileds is working to reduce the epitaxy manufacturing cost of illumination-grade LEDs by 60% by using silicon instead of sapphire, which is more expensive and harder to obtain.

5.2 Poster Session for All Current DOE-Funded Manufacturing SSL R&D Projects

At an evening poster session and reception sponsored by the Next Generation Lighting Industry Alliance (NGLIA), workshop attendees had an opportunity to talk with all 10 SSL manufacturing R&D award recipients one on one. Earlier during the workshop, Keith Cook of Philips gave some background on NGLIA, an alliance of for-profit corporations formed to promote the understanding, implementation, and adoption of semiconductor light sources in specialty and general lighting systems. Cook also invited attendees to participate in an NGLIA survey of employment and job growth in the U.S. SSL industry.

The reception also included a poster and demonstration of a Cost Model for LED Package Manufacturing, developed by a DOE working group and presented by Steve Bland from SB Consulting. Another poster, presented by Mary Ashe from Navigant Consulting, highlighted key findings from Part 1 of a three-part DOE study to assess the life-cycle environmental impact in the manufacture, transport, use, and disposal of LED lighting products. The poster session and reception provided attendees with additional opportunities for discussion, information exchange, and potential partnering.



The evening poster session and reception allowed for additional, in-depth discussion of the R&D projects presented earlier in the day.

6. DOE's SSL Manufacturing R&D Roadmap

6.1 Updating the Roadmap

Fred Welsh of Radcliffe Advisors previewed the proposed updates to the DOE SSL Manufacturing R&D Roadmap, which were based on feedback from a series of roundtable discussions held in April and May of 2012 and attended by more than two dozen industry experts. The insights of these experts guided the development of proposed priority tasks for DOE's roadmap. To view the roundtable reports, visit www.ssl.energy.gov/techroadmaps.html.

The proposed priority tasks for LEDs included flexible manufacturing of state-of-the-art modules, light engines, and luminaires; improved manufacturing of phosphors or other down-converters; and high-speed, high-resolution, nondestructive test equipment and metrics for each stage of production. Proposed OLED priority tasks included high-speed, low-cost, uniform deposition of OLED layers and structures; improved quality and yield to achieve lower cost, with an emphasis on tolerances and process windows; and low-cost integrated substrates and encapsulation materials.

6.2 Participants Provide Input on DOE R&D Priorities

The attendees split up into separate LED and OLED track sessions. Invited speakers—most of them from the April and May roundtables—provided brief presentations to introduce the key topics and issues for discussion. The LED track session explored key barriers to manufacturing low-cost, high-quality LED products, examining challenges and opportunities throughout the supply chain. The speakers included James Zahler of GT Advanced Technologies, Jim Neff of Philips Lumileds,

Eric Haugaard of Cree, Inc., and Steve Paolini of NEXT Lighting. The OLED track session explored opportunities for cost savings in the fabrication of OLED panels, critical components, and manufacturing tools, and discussed the integration of OLED panels into distinctive luminaires. The speakers included Michael Boroson of OLEDWorks, David Newman of Moser Baer Technologies, Jim Dietz of Plextronics, and Dennis O'Shaughnessy of PPG Industries.

Later, attendees split into even smaller groups that each focused on a specific priority topic. The input from these track and topic-table sessions will be used to update the SSL Manufacturing R&D Roadmap and guide DOE planning for Manufacturing R&D solicitations. DOE expects to publish the updated Roadmap in August and to issue the next Manufacturing R&D solicitation later in 2012.

Input reported from the track and topic-table sessions will be used to update the SSL Manufacturing R&D Roadmap and guide DOE planning for future solicitations.

7. SSL Manufacturing in the U.S.

A panel moderated by Brodrick focused on ways to improve the U.S.'s role in the SSL supply chain. Robert Petersen of GE Lighting discussed what his company is doing from a luminaire perspective to increase the flexibility of the supply chain by doing more of its manufacturing domestically. He noted that long, overseas-based supply chains require large, stocked inventories because customer demand is hard to predict—but because SSL product life-cycles are short, unsold products quickly become out of date. Petersen described how GE started with U.S. assembly and standardized the platforms. He said despite fierce competition, GE thinks it can be competitive manufacturing in the U.S. by providing value to its customers. Petersen suggested that DOE could help by making funding available for large investments based on job creation, because many companies are focused on return on investment when making financial decisions.

Careful planning and government help have enabled China to achieve 25% of the world's epitaxy capacity.

Bill Quinn of Veeco Instruments offered an equipment manufacturer's perspective on the same topic, informed by the results of an informal survey he conducted, in which five manufacturers and SEMI were asked what factors cause manufacturing to exit the U.S., and what can be done to stop the exodus. He recounted how China has achieved 25 percent of the world's LED epitaxy capacity over the past five years as a result of a strategy that includes subsidies for LED lighting on the consumer side, and free land, tax incentives, and a 17 percent value-added tax on imported semiconductors on the manufacturing side. Quinn called for more science, technology, engineering, and math education in the U.S. so that companies like Veeco can find the new talent they need in order to successfully compete. He also cited the need for government support of LED-specific equipment projects.

Michele Ricks of EMD Chemicals, an affiliate of Merck KGaA, focused on expanding the role of the U.S. in the global SSL supply chain through collaborative projects between equipment makers and material makers, as well as between industry and universities. She advocated fostering an environment for collaboration between industry, research institutions, and universities—something that she noted is done in other countries. One problem Ricks identified is that in the U.S., engineers and scientists are not valued as highly as are those in some other professions. She advocated that the U.S. government provide incentives for long-term investment in innovation and fund low-cost strategies to enable local manufacturing. Such efforts, she said, will have a "grassroots effect," because the more innovation there is here, the more likely innovators will want to keep manufacturing here.

Question-and-Answer Session

An audience member made the point that once consumers understand that LED lighting is easy to integrate into homes and businesses, more people would be willing to purchase it and find creative ways to use it. Petersen replied that while education will definitely help, first cost has to come down. "It's about somebody opening up their pocketbook," he said. Another attendee wondered whether so much emphasis on replacement lamps and first cost might be a mistake and suggested that getting consumers to think about SSL products as small appliances might be more effective. Quinn noted that with conventional lighting, consumers never had to worry about such things as color temperature, but with SSL there is a paradigm shift, and even with the help of LED Lighting Facts® it can be confusing. "There's a lot of education that's needed," he said. Responding to a suggestion that the U.S. government create demand for SSL products, Ricks cautioned that this should be done with the long term in mind, because the sudden withdrawal of government subsidies—such as what happened in Germany with photovoltaics—could hurt the industry.

8. Conclusion

Brodrick concluded the workshop by thanking participants for their input and participation. He noted the final DOE SSL workshop in 2012 will be the July Market Introduction Workshop in Pittsburgh, and encouraged attendees to stay apprised of DOE SSL program activities by visiting www.ssl.energy.gov.

Presentations and materials from the DOE SSL Manufacturing R&D Workshop are posted online at www.ssl.energy.gov/sanjose2012_materials.html.

APPENDIX A: 2012 SSL Manufacturing R&D Workshop Participants

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Kelvin Rong
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Bob Rustin
Dupont Teijin Films

Christopher Ruud
Cree, Inc.

Angel Sanjurjo
SRI International

Thomas Schuller
H.E. Williams, Inc.

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Osram Sylvania

Douglas Seymour
Osram Sylvania

David Sheh
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James Zahler
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Hongmei Zhang
Plextronics, Inc.

Mingwei Zhu
Applied Materials, Inc.

APPENDIX B: List of SSL Manufacturing R&D Project Posters

TITLE	PRESENTER/COMPANY
Development of Production PVD-AlN Buffer Layer System and Processes to Reduce Epitaxy Costs and Increase LED Efficiency	Frank Cerio Veeco Instruments
Creation of a U.S. Phosphorescent OLED Lighting Panel Pilot Facility	Mike Hack Universal Display Corporation
Process and Product Yield Management for Low Cost Integrated Manufacturing and Quality Control of OLEDs	Raj Rajeswaran Moser Baer Technologies
Roll-to-Roll Solution-Processible Small-Molecule OLEDs	Jerry Liu GE Global Research
Part 1–Driving Down HB-LED Costs: Implementation of Process Simulation Tools and Temperature Control Methods for High Yield MOCVD Growth	Jay Montgomery Veeco Process Equipment
Advanced Epi Tools for Gallium Nitride LED Devices	Vivek Agrawal Applied Materials
Integrated Automated Yield Management and Defect Source Analysis Inspection Tooling and Software for LED Manufacturing	Srini Vedula KLA-Tencor
Part 2–Driving Down HB-LED Costs: Implementation of Process Simulation Tools and Temperature Control Methods for High Yield MOCVD Growth	Mike Coltrin Sandia National Laboratories
A Low Cost Lithography Tool for High Brightness LED Manufacturing	Andy Hawryluk Ultratech
Advanced Manufacturing Methods for Warm-White LEDs for General Lighting	Anirudha Deshpande GE Lighting Solutions
A Simple Modular Cost Model for LED Package Manufacturing	Steve Bland SB Consulting
Life-Cycle Energy Consumption: Incandescent, Compact Fluorescent, and LED Lamps	Mary Ashe Navigant/PNNL
Low-Cost Illumination-Grade LEDs Enabled by Nitride Epitaxy on Silicon Substrates	John Epler Philips Lumileds